

# Detection of warm molecular hydrogen in the circumstellar disk around the Herbig Ae star HD97048

C. Martin-Zaïdi<sup>1</sup>, P.-O. Lagage<sup>1</sup>, E. Pantin<sup>1</sup> and E. Habart<sup>2</sup>

## ABSTRACT

We present high resolution spectroscopic mid-infrared observations of the circumstellar disk around the Herbig Ae star HD97048 with the *VLT Imager and Spectrometer for the mid-InfraRed* (*VISIR*). We detect the S(1) pure rotational line of molecular hydrogen ( $H_2$ ) at  $17.035 \mu\text{m}$  arising from the disk around the star. This detection reinforces the claim that HD97048 is a young object surrounded by a flared disk at an early stage of evolution. The emitting warm gas is located within the inner 35 AU of the disk. The line-to-continuum flux ratio is much higher than expected from models of disks at local thermodynamics equilibrium. We investigate the possible physical conditions, such as a gas-to-dust mass ratio higher than 100 and different excitation mechanisms of molecular hydrogen (X-ray heating, shocks, ...) in order to explain the detection. We tentatively estimate the mass of warm gas to be in the range from  $10^{-2}$  to nearly  $1 M_{Jup}$ . Further observations are needed to better constrain the excitation mechanisms as well as the mass of gas.

*Subject headings:* stars: pre-main sequence – stars: individual (HD97048) – (stars:) circumstellar matter – (stars:) planetary systems: protoplanetary disks – infrared: stars

## 1. Introduction

Circumstellar (CS) disks surrounding pre-main sequence stars are supposed to be the location of planet building. The characterization of the gaseous component, which initially

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<sup>1</sup>Laboratoire AIM, CEA/DSM - CNRS - Université Paris Diderot, DAPNIA/Service d'Astrophysique, Bat. 709, CEA/Saclay, 91191 Gif-sur-Yvette Cedex, France, claire.martin-zaidi@cea.fr, pierre-olivier.lagage@cea.fr, epantin@cea.fr

<sup>2</sup>Institut d'Astrophysique Spatiale, 91405 Orsay, France, emilie.habart@ias.u-psud.fr

represents 99% of the total disk mass, is a key research question towards an understanding of protoplanetary disks and planet formation. However, from previous observations, little is known about the gas compared to the dust. Major questions concerning planet formation remain. How massive are the disks? Can giant planets form in every disk? How long does the planet formation process take? Detailed information is required about the gas in disks in order to address these questions. In particular, characterizing the warm gas phase in the inner disk ( $R < 50$  AU), where planet formation is supposed to take place, is an essential step.

Molecular hydrogen ( $H_2$ ) is the main constituent of the molecular cloud from which the young star is formed and is also expected to be the main component of the CS disk. It is expected to be at least  $10^4$  times more abundant than other gas tracers such as carbon monoxide (CO) (e.g. Bell et al. 2006), since it self-shields very efficiently against photodissociation by far-ultraviolet (FUV) photons and does not freeze effectively onto grain surfaces.  $H_2$  is the only molecule that can directly constrain the mass reservoir of warm and hot molecular gas in disks. Indeed, the detection of  $H_2$  excited by collisions allows us to measure the temperature and density of the warm gas. Unfortunately, direct observation of  $H_2$  is difficult. Electronic transitions occur in the ultraviolet to which the Earth's atmosphere is opaque, and rotational and ro-vibrational transitions at infrared (IR) wavelengths are faint because of their quadrupolar origin. FUV absorption lines have been observed with the *FUSE* satellite in the spectrum of some Herbig Ae stars (HAes) and show the presence of warm ( $T_{gas} > 300$  K) molecular hydrogen gas in the CS environment of these stars (Martin-Zaïdi et al. 2007). However, absorption observations require specific configurations to observe the gas within the disks, i.e. nearly edge-on. Due to the high inclination angles to the lines of sight estimated for the disks observed by Martin-Zaïdi et al. (2007), the detected  $H_2$  is not in the disk. Those authors concluded that the lines of sight probably pass through a thin layer of warm/hot gas above the surface of the disk which is produced by the photoevaporation of the disk. Searches for mid-IR  $H_2$  rotational emission lines have been performed using different space- and ground-based instruments. Space-based instruments on ISO and Spitzer have low spectral and spatial resolution, and therefore have not yielded an unambiguous detection of  $H_2$  line emission from protoplanetary disks (Thi et al. 2001; Pascucci et al. 2006). Indeed, when detections of  $H_2$  towards a few pre-main sequence stars have been claimed with ISO-SWS (Thi et al. 2001), ground-based observations showed that contamination from surrounding cloud material was important and that ISO detections were likely not dominated by the emission of the disk gas (e.g. Richter et al. 2002; Sako et al. 2005). Recently, Carmona et al. (2007) estimated the line-to-continuum ratio that should be observed for  $H_2$  transitions in the mid-IR. They used a two-layer model (Chiang & Goldreich 1997; Dullemond et al. 2001) of a gas-rich disk (column density of  $N(H_2) = 10^{23} \text{ cm}^{-2}$ ) seen face-on, located at 140 pc from the Sun, with local thermodynamics equilibrium (LTE) for the gas and dust,  $T_{gas} = T_{dust}$ , and

assuming a gas-to-dust mass ratio about 100. Those authors concluded that the expected peak flux of the S(1) line at  $17.035\ \mu\text{m}$ , observed at a spectral resolution of 20 000, should be less than 0.3% of that of the continuum at temperatures higher than 150 K, and thus should not be observable with the existing instruments. Indeed, they did not detect any  $\text{H}_2$  mid-IR emission line in their sample of 6 Herbig Ae stars.

However,  $\text{H}_2$  rotational lines have been recently detected in the disk around one Herbig Ae star, namely AB Aur, with the high spectral and spatial resolution TEXES spectrometer (Bitner et al. 2007). These detections imply that  $\text{H}_2$  can be observed in the mid-IR domain when particular physical conditions exist in disks.

The *VLT Imager and Spectrometer for the mid-InfraRed* (*VISIR*; Lagage et al. 2004) has the high spectral ( $10\,000 < R < 30\,000$ ) and spatial resolution necessary to pick up such narrow gas lines from the disks. In addition, high spectral resolution is a key element to disentangle the  $\text{H}_2$  line from the absorption lines due to the Earth’s atmosphere. The spectral ranges covered by *VISIR* offer access to the most intense pure rotational lines of molecular hydrogen ( $\text{H}_2$ ): S(1) ( $v = 0 - 0, J = 3 - 1$ ) at  $17.0348\ \mu\text{m}$ , S(2) ( $v = 0 - 0, J = 4 - 2$ ) at  $12.2786\ \mu\text{m}$ , S(3) ( $v = 0 - 0, J = 5 - 3$ ) at  $9.6649\ \mu\text{m}$ , and S(4) ( $v = 0 - 0, J = 6 - 4$ ) at  $8.0250\ \mu\text{m}$ . The S(0) ( $v = 0 - 0, J = 2 - 0$ ) transition near  $28\ \mu\text{m}$  is not observable from the ground due to the Earth’s atmospheric absorption.

A particularly interesting object to study the CS material around a pre-main sequence intermediate mass star is HD97048. HD97048 is a nearby, relatively isolated Herbig A0/B9 star located in the Chameleon cloud at a distance of 180 pc (van den Ancker et al. 1998). Its age has been estimated from evolutionary tracks to be of the order of 3 million years (kindly computed by L. Testi and A. Palacios). This star is known to be surrounded by an extended CS disk. The *VISIR* imaging observations of this star conducted in 2005 June 17 and 19, have revealed an extended emission of PAHs (Polycyclic Aromatic Hydrocarbons) at the surface of a flared disk inclined to the line of sight by  $42.8^{+0.8}_{-2.5}$  degrees (Lagage et al. 2006). This is the only Herbig star for which the flaring of the disk has been observed by direct imaging. The flaring index has been measured to be  $1.26 \pm 0.05$ , in good agreement with hydrostatic flared disk models (Lagage et al. 2006; Doucet et al. 2007). This geometry implies that a large amount of gas should be present to support the flaring structure and that the disk is at an early stage of evolution. This star is thus one of the best candidates to study the gas component in the disks of HAe stars.

In this paper, we present *VISIR* observations of the S(1) pure rotational emission line of molecular hydrogen at  $17.03\ \mu\text{m}$  arising from the disk of HD97048.

## 2. Observations and data reduction

HD97048 was observed for 1800s with the high spectral resolution long-slit mode of *VISIR* in June 22, 2006. The central wavelength of the observation was set to  $17.035\ \mu\text{m}$ . We used the  $0.75''$  slit, providing a spectral resolution about 10 000, i.e.  $\Delta v=30\ \text{km s}^{-1}$ .

The weather conditions were very good and stable during the observations; the optical seeing was less than  $0.66''$  and the airmass ( $<1.8$ ) was close to the minimum airmass accessible when observing this object from the Paranal ESO observatory. The standard "chopping and nodding" technique was used to suppress the large sky and telescope background dominating at mid-infrared wavelengths. Secondary mirror chopping was performed in the North-South direction with an amplitude of  $8''$  at a frequency of 0.025 Hz. Nodding technique, necessary to compensate for chopping residuals, was applied using a telescope offset of  $8''$  in the South direction, every 3 minutes. The pixel scale is  $0.127''/\text{pixel}$  resulting in a total field of view along the slit about  $32.5''$ . The elementary frames were combined to obtain chopping/nodding corrected data. *VISIR* detector is affected by stripes randomly triggered by some abnormal high-gain pixels. A dedicated destriping method has been developed to suppress them (Pantin 2007, in preparation). In order to correct the spectrum from the Earth's atmospheric absorption and obtain the absolute flux calibration, we observed the CERES asteroid and the standard star HD89388 (see [www.eso.org/VISIR/catalogue](http://www.eso.org/VISIR/catalogue)) just before and after observing HD97048. HD89388 and CERES were observed at nearly the same airmass and seeing conditions as the object. As shown in Fig. 1*b*, airmasses are slightly different between the observation of CERES and that of HD97048. However, the discrepancy between the two spectra of the sky cannot be responsible for the emission feature we observe in the HD97048 spectrum around  $17.035\ \mu\text{m}$ , i.e. the  $\text{H}_2$  line (Fig. 1*a*). We thus have divided the spectrum of HD97048 by that of CERES (which has a much better signal-to-noise ratio than that of the standard star HD89388) to correct for the telluric absorption, and used the HD89388 observed and modelled spectra (Cohen et al. 1999) to obtain the absolute flux calibration. The wavelength calibration is done by fitting the observed sky background features with a model of the Paranal's atmospheric emission.

We note that Valenti et al. (2000) found  $A_v=0.24\ \text{mag}$  from the fit of the *IUE* spectrum of HD97048, thus we have not corrected the spectrum for dust extinction, since it is neglectible in our wavelength range for  $A_v < 40\ \text{mag}$  (Fluks et al. 1994).

### 3. Results

As shown in Fig. 2a, we have detected the  $\text{H}_2$  pure rotational S(1) line near  $17.03 \mu\text{m}$ . In the flux-calibrated spectrum, the standard deviation ( $\sigma$ ) of the continuum flux was calculated in regions less influenced by telluric absorption, and close to the feature of interest. We deduced a  $6\sigma$  detection in amplitude for the line, corresponding to a signal-to-noise of about  $11\sigma$  for the line, when integrating the signal over a resolution element (6 pixels). The line is not resolved as we can fit it with a Gaussian with a full width at half maximum equal to a spectral resolution element of  $30 \text{ km s}^{-1}$  (see Fig. 2a). From our fit, assuming the emission arises from an isothermal mass of optically thin  $\text{H}_2$ , we derived an integrated flux in the line of  $2.4 \times 10^{-17} \text{ W m}^{-2}$  or  $2.4 \times 10^{-14} \text{ ergs s}^{-1} \text{ cm}^{-2}$ .

Once the spectrum is corrected from the Earth’s rotation, and knowing the heliocentric radial velocity of HD97048 ( $+21 \text{ km s}^{-1}$ ; Acke et al. 2005), we estimated, from the wavelength position of the Gaussian peak, the radial velocity of  $\text{H}_2$  to be about  $4 \pm 2 \text{ km s}^{-1}$  in the star’s rest frame. We thus considered that the radial velocity of the  $\text{H}_2$  is similar to that of the star, implying that the emitting gas is bound to the star. The  $\text{H}_2$  line is not resolved spatially. Given the *VISIR* spatial resolution of about  $0.427''$  at  $17.03 \mu\text{m}$ , and the star distance (180 pc from the sun), we can assess that the emitting  $\text{H}_2$  is located within the inner 35 AU of the disk (Fig. 2b). We estimated the corresponding column densities and masses as a function of prescribed temperatures (Table 1). For this purpose, we first assumed that the line is optically thin and that the radiation is isotropic. In this context, assuming that the first rotational levels (up to  $J = 3$ ) of  $\text{H}_2$  are thermalized, and thus that their populations follow the Boltzmann law for a given temperature (LTE), the column densities are derived from the following formula:

$$I_{ul} = \frac{hc}{4\pi\lambda} N_u(\text{H}_2) A_{ul} \quad \text{ergs s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1} \quad (1)$$

where  $I_{ul}$  is the integrated intensity of the line,  $\lambda$  is the wavelength of the transition  $J = u - l$ ,  $A_{ul}$  is the spontaneous transition probability,  $N_u(\text{H}_2)$  is the column density of the upper rotational level of the transition. Since the line is not spatially resolved, we calculated a lower limit on  $I_{ul}$  by dividing the integrated flux value by the solid angle of the point spread function, and thus obtained lower limits on the total column densities. Under the same assumptions as used for the calculations of the column densities and assuming that the medium we observe is homogeneous, the mass of warm  $\text{H}_2$  is given by (Thi et al. 2001):

$$M_{gas} = f \times 1.76 \times 10^{-20} \frac{F_{ul} d^2}{(hc/4\pi\lambda) A_{ul} x_u(T)} M_{\odot} \quad (2)$$

where  $F_{ul}$  is the line flux,  $d$  the distance in pc to the star,  $x_u(T)$  is the fractional population of the level  $u$  at the temperature  $T$  in LTE (for details on the calculation method, see van Dishoeck 1992),  $f$  is the conversion factor required for deriving the total gas mass from the H<sub>2</sub>-ortho or H<sub>2</sub>-para mass. Since  $M_{H_2} = M_{H_2}(\text{ortho}) + M_{H_2}(\text{para})$ ,  $f = 1 + 1/(\text{ortho}/\text{para})$  for the S(1) line (a H<sub>2</sub>-ortho transition). The equilibrium ortho-para ratio at the temperature  $T$  was computed using Takahashi & Uehara (2001).

We also estimated the dust mass producing the flux level of the continuum in the spectrum. We used a simple model of optically thin emission of a given mass of dust at the surface of a disk. The grains have sizes between 0.01 and 100  $\mu\text{m}$  and a size distribution following a power-law with an index of -3.5. A fixed composition, mixture of amorphous silicates (50%) and amorphous carbon (50%) is assumed. For different temperatures (150, 300, 1000 K) assigned to the dust, we computed the corresponding mass of dust and derived gas-to-dust mass ratios. Our results are tabulated in Table 1.

#### 4. Discussion

Our high resolution spectroscopic observation of the S(1) pure rotational line of H<sub>2</sub> at 17.03  $\mu\text{m}$  of HD97048 has revealed the presence of significant amounts of warm gas in the inner 35 AU of the disk. From a gaussian fit of the emission line, we derived very high column densities of warm gas, which are more than two orders of magnitude higher than those generally observed in the CS environment of Herbig Ae stars (Martin-Zaïdi et al. 2007). This confirms that HD97048 is a young object surrounded by a circumstellar disk at an early stage of evolution. Indeed photoevaporation of the gas is expected to clear up the inner part of the disk within 3 million years (Takeuchi et al. 2005).

We derived masses of the warm gas in the range from  $10^{-2}$  to nearly 1  $M_{Jup}$  ( $1 M_{Jup} \sim 10^{-3} M_{\odot}$ ) depending on the adopted temperature, and assuming LTE. The masses derived here are lower than those of Lagage et al. (2006) who have estimated a minimum mass of gas in the inner disk to be of the order of 3  $M_{Jup}$ . But it should be pointed out that mid-IR H<sub>2</sub> lines are only probing warm gas located in the surface layer of the disk, when a higher mass of colder gas is expected to be present in the interior layers of the disk. In any case, the finding of warm molecular hydrogen reinforces the claim that a large amount of cold gas is present in the disk to support its flaring geometry (Lagage et al. 2006).

It is generally accepted that the first rotational levels ( $J$ ) of  $H_2$  are populated by thermal collisions, an excitation mechanism which requires kinetic temperatures higher than 150 K to produce the S(1) transition. Assuming equal dust and gas temperatures, we estimated dust masses responsible for the continuum emission and derived gas-to-dust mass ratios in the range from 3260 to 14164 (Table 1), much larger than the canonical value of 100. These crude estimates are in agreement with more sophisticated models such as two-layer LTE disk models (Carmona et al. 2007). Indeed, by scaling the gas-to-dust mass ratio found here to the canonical value of 100, we obtained a peak line flux of about 0.46% of that of the continuum at 150 K, decreasing to 0.1% of the continuum at 1000 K, which is close to the line-to-continuum ratios calculated in disks models by Carmona et al. (2007). Thus one possible interpretation of our observation is that the dust is partially depleted from the disk surface layer, where the  $H_2$  emission originates. The spatial decoupling between the gas and the dust may be due to dust settling or dust coagulation into larger particles.

However, other excitation mechanism cannot be excluded. Several competing mechanisms could contribute to the excitation of molecular hydrogen such as UV pumping, shocks, X-rays, etc..., (see review papers by Habart et al. 2004; Snow & McCall 2006) and could be responsible for the observed emission. Weak X-ray emission has been detected from HD97048 by ROSAT (Zinnecker & Preibisch 1994). X-rays and UV photons are likely candidates to heat the gas to temperatures significantly higher than those of the dust (Glassgold et al. 2007) and could partly explain a high line-to-continuum ratio. According to radiative transfer models of disks around T Tauri stars (Nomura & Millar 2005; Nomura et al. 2007), X-ray heating could significantly increase the line-to-continuum flux ratio, but, applying the same increase factor to HAes, the S(1)  $H_2$  line would still be below the detection limit of *VISIR*.

Note that the present *VISIR* observation does not allow us to discriminate between the different possible physical origins of the emission of  $H_2$ . New observations of HD97048 will be performed with *VISIR* in order to observe the other pure rotational lines of  $H_2$ . The detection of these lines would help to better constrain the temperature (and thus the mass) of the warm gas.

Our results are very similar to those obtained by Bitner et al. (2007) for AB Aur with the TEXES instrument. Indeed, those authors have shown that the emitting warm gas is located in the inner 18 AU of the disk around AB Aur. For the two stars, the gas has not completely dissipated in the inner region of the disk in a lifetime of about 3 Myrs. HD97048 and AB Aur have nearly identical astrophysical parameters ( $T_{\text{eff}}$ , age, mass, distance). Their disks are flared (Pantin et al. 2005; Lagage et al. 2006) and seem to be in similar evolutionary states, which could well be a disk old enough such that the dust sedimentation/coagulation has already been at work, but young enough such that the gas has not yet been photoevapo-

rated. It is not possible to draw definite conclusions with only two examples and it would be interesting to observe other HAe stars similar to AB Aur and HD97048. The high angular resolution and high spectral resolution available with ground-based instruments are key advantages over space-based instruments such as ISO-SWS in order to obtain firm detections of H<sub>2</sub> from disks.

This work is based on observations obtained at ESO/VLT (Paranal) with *VISIR*, program number 077.C-0309(B). We would like to thank S. Madden for her careful reading of the manuscript. CMZ warmly thanks C. Gry, C. Doucet, P. Didelon and A. Carmona for fruitfull discussions.

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Table 1: Total column density and mass of H<sub>2</sub>, mass of dust and gas-to-dust mass ratio as a function of the temperature.

	150 K	300 K	1000 K
N(H <sub>2</sub> ) (cm <sup>-2</sup> )	$>2.19 \times 10^{23}$	$>1.41 \times 10^{22}$	$>3.27 \times 10^{21}$
M(H <sub>2</sub> ) (M <sub>Jup</sub> )	$7.37 \times 10^{-1}$	$4.51 \times 10^{-2}$	$1.33 \times 10^{-2}$
M <sub>dust</sub> (M <sub>Jup</sub> )	$2.23 \times 10^{-4}$	$1.03 \times 10^{-5}$	$9.39 \times 10^{-7}$
gas-to-dust mass ratio	3260	4378	14164

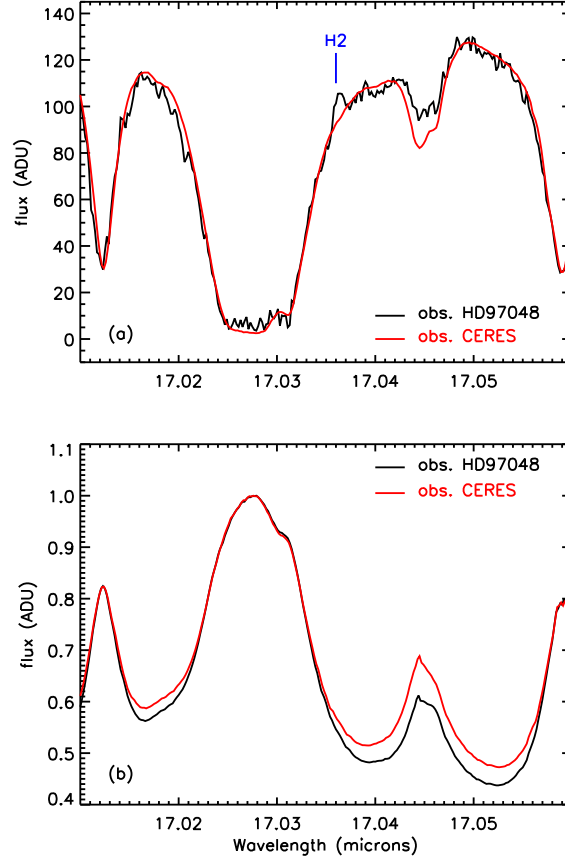


Fig. 1.— (a): *VISIR* spectrum of the CERES asteroid (red) overplotted on the HD97048 spectrum (black). (b): Spectrum of the sky during the observations of HD97048 and CERES.

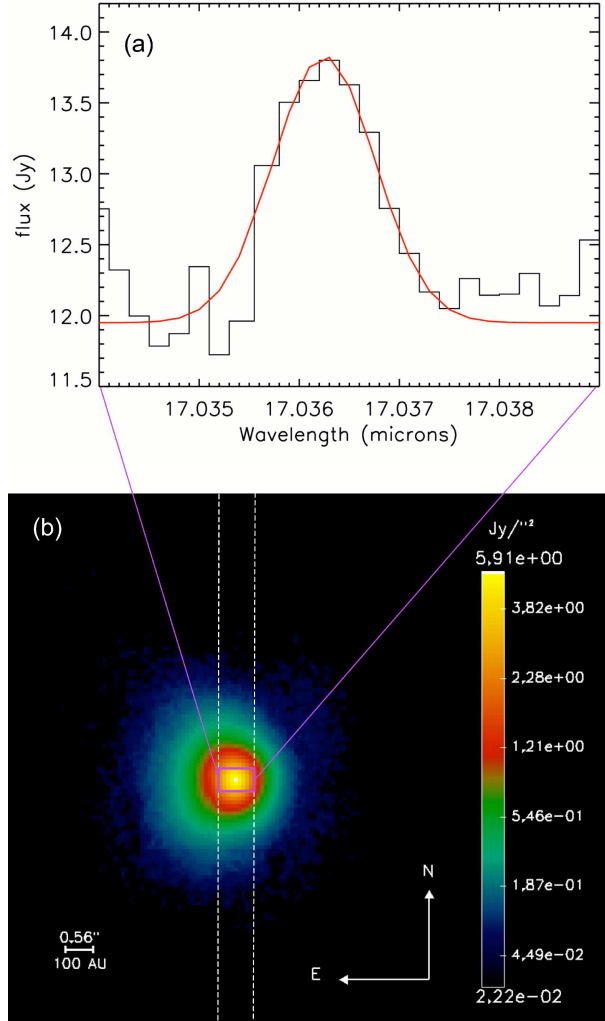


Fig. 2.— (a): S(1)  $\text{H}_2$  emission line from HD97048 disk, observed with the high spectral resolution mode of *VISIR*. Black line: observed spectrum corrected for telluric absorption. Red line: fit of a gaussian with FWHM equal to a spectral resolution element. Here the spectrum has not been corrected for the Earth’s rotation. (b): *VISIR* false-color image of the emission from the CS material surrounding HD97048 (Lagage et al. 2006). White dotted lines: position of the 0.75'' slit of the spectrograph during the observation of  $\text{H}_2$  emission. Purple rectangle: one element of spatial resolution (diffraction limited). As the line is not spatially resolved, the  $\text{H}_2$  emission arises within this element.